Vanishing of Capillary Hysteresis in Porous Media

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RESEARCH OBJECTIVES

The degree of water saturation (S) exerts strong influences on water flow, transport of solutes and heat, and mechanical properties of porous media. The monotonic decrease of the matric potential (ψ) with decreased saturation reflects the combination of capillary and adsorptive influences in lowering the free energy of soil water. In the early decades of soil physics, it was assumed that the S(ψ) relation in a given system represented a series of unique equilibrium conditions. Since the classic 1930 paper of Haines, hysteresis in S(ψ) has been regarded as a basic aspect of interactions between water and variably saturated porous media. At any given potential, the equilibrium saturation level obtained by draining a system is greater than or equal to that obtained by wetting an initially dry system to the same potential. In an attempt to gain a better understanding of the hysteresis phenomenon, we consider conditions that lead to its disappearance.

APPROACH

Capillary models and Miller-Miller unsaturated hydraulic scaling were used to predict conditions necessary for removal of hysteresis. Disappearance of hysteresis was tested through suction plate measurements of drainage and wetting curves for sands and gravels, with grain sizes ranging from 0.2 to 14 mm. The influence of surface tension was tested through measurements of S(ψ) in 7 mm gravel, with and without a surfactant—sodium dodecylbenzenesulfonate (SDBS).

ACCOMPLISHMENTS

Calculations based on a simple pore-size model lead to the predicted disappearance of hysteresis in the grain-size range of 8 to 15 mm. A more constrained predicted grain-size limit of 10.4 ± 0.5 mm was obtained by applying Miller-Miller scaling to a conceptual model of Haines. More generally, hysteresis is also predicted to depend on surface tension, fluid densities, and acceleration. Laboratory measurements showed that hysteresis loops remain well defined for grain sizes up to 7 mm. At a grain size of 9 mm, hysteresis is barely detectable. For grain sizes equal to or greater than 10 mm, hysteresis is not observed. Measurements of S(ψ) on 7 mm gravels exhibited hysteresis without SDBS, but did not exhibit hysteresis with it. These results support our general analysis, which predicted elimination of hysteresis based on fluid densities, acceleration, grain size, and surface tension. These parameters combine to yield the dimensionless Haines number, with a critical value of 14.8 ± 1.4. Above this value, capillary hysteresis is not possible.

SIGNIFICANCE OF FINDINGS

The experiments completed in this project support the predicted grain-size and surface-tension dependence of capillary hysteresis, and show that hysteresis is not a fundamental feature of unsaturated porous media. Lack of previous awareness of nonhysteretic S(ψ) appears to result from the fact that the considered combinations of grain size, surface tension, fluid densities, and acceleration were within the realm in which capillary rise is greater than the grain size. Studies on unsaturated media conducted with surfactants and/or in centrifuges may benefit from this work.

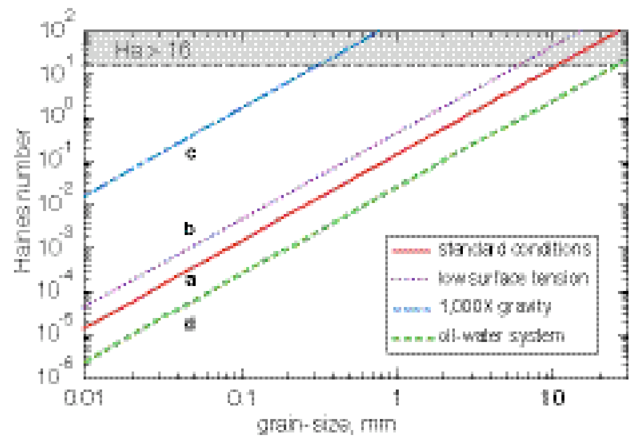

Figure 1. The Haines number is comprised of fluid-fluid density differences and surface tension, acceleration, and grain-size. Grain-size dependence of the Haines number for (a) standard conditions (air-water, ordinary gravity), (b) low surface tension (surfactant solution, ordinary gravity), (c) much higher body force (air-water, 1,000g centrifuge), and (d) an oil-water system conditions (ordinary gravity). The horizontal line at *Ha* = 16 separates systems that do and that do not exhibit hysteresis.

RELATED PUBLICATIONS

Tokunaga, T.K., J. Wan, and K.R. Olson. Saturation-matric potential relations in gravel. Water Resour. Res. 38(10), 1214, doi:10.1029/2001WR001242, 2002.

Tokunaga, T.K., K.R. Olson, and J. Wan. Moisture characteristics of Hanford gravels: Bulk, grain-surface, and intragranular components. Vadose Zone J., 2003 (in press).

ACKNOWLEDGMENTS

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